Galaxy Substructure and Satellites

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For each subhalo, we calculate a number of physical properties, such as the maximum circular velocity, spin and velocity dispersion, and the particle group as a genuine subhalo in our group catalogue. Provided more than 20 bound particles remain, we record the information about the local dark matter 'temperature' in a slice of thickness 13.7 Mpc through the full box (137 Mpc on a side) of the parent simulation, centred on the 'Aq-A' halo that was selected for resimulation. The other five panels show this halo resimulated at different resolutions. In these panels, all particles within a cubic box of side length 2 × 5000000000 are shown, and the circles mark the radius r500, which is useful for tracking subhaloes between simulation outputs.

For all these simulations we also stored at least 128 outputs, however we focus on an analysis of the objects at redshift 0.0000 – 0.0000 with the same colour map as in Figure 2. Further images and videos of the formation process of the halos of galactic halos at redshift z = 0 are available at http://www.mpa-garching.mpg.de/aquarius.

In Figures 2 and 3, we show images of the dark matter density, and the colour hue encodes the local part of the particle velocity, weighted as the mean dark matter velocity dispersion, along the line of sight, and the local dark matter velocity dispersion, weighted as

\[ \rho(r,z) \approx \frac{1}{V} \int \int \int \rho(z) dV. \]

The colour hue information is orthogonal to the brightness information; when converted to black and white, only the density information remains, while the colour hue encodes the local particle velocity dispersion weighted by the mean dark matter velocity dispersion.
Dark Matter Subhalo Mass Function

**Figure 6.** Differential subhalo abundance by mass in the 'A' halo within the radius $r_{50}$. We show the count of subhaloes per logarithmic mass interval for different resolution simulations of the same halo. The bottom panel shows the same data but multiplied by a factor $M_{2\text{sub}}$ to compress the vertical dynamic range. The dashed lines in both panels show a power law $dN/dM \propto M^{-1.9}$. For each of the resolutions, the vertical dotted lines in the lower panel mark the masses of subhaloes that contain 100 particles.

**Figure 5.** Local logarithmic slope of the density profiles as a function of radius for the Aq-A halo simulated at different numerical resolution. Only the radial region that should be converged according to the criteria of Power et al. (2003) is shown. Note that the large fluctuations in the outer parts are caused by substructures but nevertheless reproduce well between simulations. In this regime, we expect significant halo-to-halo scatter.

**Figure 4.** Spherically averaged density profile of the Aq-A halo at $z=0$, at different numerical resolutions. Each of the profiles is plotted as a thick line for radii that are expected to be converged according to the resolution criteria of Power et al. (2003). These work very well for our simulation set. We continue the measurements as thin solid lines down to $2\epsilon$, where $\epsilon$ is the Plummer-equivalent gravitational softening length in the notation of Springel et al. (2001b). The dotted vertical lines mark the scale $2^{8}\epsilon$, beyond which the gravitational force law is Newtonian. The mass resolution changes by a factor of 1835 from the lowest to the highest resolution simulation in this series. Excellent convergence is achieved over the entire radial range where it is expected.
What about the galaxies?


- Supernova Feedback (White & Rees 1978, Kauffmann et al. 1993)

- Need to go beyond simplified models
  - Cosmic Ray pressure (Wadephul & Springel 2011)
What is required of the models?

Models must match several key observables:

- Global luminosity function of satellite galaxies
- Metallicity of individual satellites
- Internal kinematics
Luminosity function

Example: Inhomogeneous reionization

Metallicity distribution

Example: Global, Local Reionization + SN Feedback

Central mass densities

Status: semi-analytic models

- Current models broadly match the data
  - Scaling relations
- Challenge: Incorporate detailed physics & hydrodynamics
- Challenge: Simultaneously match all data sets
- Model-Independent tests
  - kinematics
Model-Independent test: Kinematics

- Magellanic Clouds have circular velocities ~ 50 km/s
  - ~10% chance of their existence (Boylan-Kolchin et al. 2010, Busha 2011)
- What are the circular velocities of the dwarf spheriodals?

![Graph showing the relationship between the number of subhalos and circular velocity.](Moore et al. 1999, Klypin et al. 1999)
Dark Matter Cores/Cusps

- Perhaps DM cores are better model than DM cusps (e.g., Goerdt et al., 2006, Gilmore et al., 2007)

- Models with core sizes of ~ 100 pc match the kinematics of dSphs (Angus & Diafero, 2009)

- Presence of cores may indicate exotic dark matter properties (e.g. tremaine & gunn 1978)
Is theory consistent with data?

- Consider a subhalo in simulation (Aquarius)
- Imagine a galaxy with the stellar density profile lives there
- Predict velocity dispersion (assuming isotropy)
- Compare with observed velocity dispersion
- Test goodness-of-fit
Photometry

Leo I

Fornax

Radius [arcmin]

Surface Density [Norm. arbitrary]

Sex

Stellar density

Strigari, Frenk, White, MNRAS 2010
Their measurement error. With these assumptions, \( \hat{v} \) is negligible and that the actual velocities are uncorrelated with each other. We then determine the quantity, and approximating the sampling distributions of the line-of-sight velocity dispersion profile, \( \sigma_v \). Given an estimate of the intrinsic velocity dispersion \( \sigma_v \), we can quantify whether it actually provides an acceptable fit to the observed counts. We then check whether the final column gives the value of \( \chi^2 \) for our preferred fits to their star count profiles, as shown in Table 1.

Figure 2 compares the observed velocity dispersion profiles of Milky Way satellites with the line-of-sight velocity dispersion predicted for each of the satellites we consider by inserting the subhalo that best matches the line-of-sight velocity dispersion profile of each satellite based on Eq. 8, we step through all the subhalos in the six Aquarius simulations to determine which subhalo has the (spherically averaged) potential that best describes the data. Specifically, for each Aquarius subhalo, we derive a spherical potential from the mass profile of our five satellites to those predicted by Eq. 2 when a subhalo that fits best according to the criterion of negligible velocity anisotropy and for the model stellar density profile with negligible velocity anisotropy, is embedded in the Milky Way. In this section we turn to the implementation of the algorithm of each satellite under the assumption of negligible velocity anisotropy and with negligible velocity anisotropy, is embedded in the Milky Way. In this section we turn to the implementation of the algorithm of each satellite under the assumption of negligible velocity anisotropy and with negligible velocity anisotropy, is embedded in the Milky Way.
The results of this exercise are shown in Fig. 5. The fits fairly well can be taken as an indication that anisotropic models predict very little kurtosis in almost all annuli, and the predicted distributions are probably weak.

For data and the normal distribution, the kurtosis is defined so that a Gaussian model gives a value of zero. In each panel, a solid curve shows the theoretical distribution of the line-of-sight velocity relative to the galaxy center, and the data are shown as a histogram. The kurtosis of these distributions is expected to be quite sensitive to velocity anisotropy, so the fact that our model fit fairly well can be taken as an indication that anisotropy is probably weak.
Status: Satellites & LCDM

- Core/Cusp issue ok
  - Necessary to improve photometry & kinematics
  - Alternative theory models (i.e. WDM)

- Dwarf Spheroidals circular velocities: 10-30 km/s.
  - Where are the visible objects with circular velocity 30-50 km/s?
  - Too few observed bright satellites problem

- Dark objects are lurking out there...
  - Gravitational lensing
  - Particle annihilation
Lensing of CDM Subhalos

- Flux ratios of multi-lensed images- (Mao & Schneider, Dalal & Kochanek)
- CDM surface densities too small for lensing effects (Xue et al, Aquarius)
- Detection of dark substructure- (Vegetti et al. 2009)
- Time delays (Keeton & Moustakas 2009)
- Hope for detecting in Galaxy?

D. Xu et al., MNRAS, 398, 1235
WIMPs in satellite galaxies

\[
\text{Flux} = \left\{ \int_0^{\Delta \Omega} \left\{ \int_{\text{LOS}} \rho^2 [r(\theta, D, s)] ds \right\} d\Omega \right\} \left\{ \int_{E_{\text{th}}}^{M_X} \sum_i \frac{dN_{\gamma,i}}{dE} \frac{\langle \sigma v \rangle_i}{M_X^2} dE \right\}
\]
Satellites & Dark Matter Detection

Fig. 2.— Uncertainty on the predicted dark matter annihilation luminosity from a dwarf galaxy (including only astrophysical uncertainties from the mass modeling, not the unknown particle physics) as a function of the number of stellar velocity measurements. While the uncertainty hits a floor of $\sim 25\%$ for large data sets, our current small samples mean that the uncertainties can be greatly reduced by additional observations.
Fig. 3.— mSUGRA (upper left), MSSM (upper right), Kaluza-Klein UED (lower left) and Anomaly mediated (lower right) models in the $(m_{\text{wimp}}, \langle \sigma v \rangle)$ plane. All mSUGRA and MSSM models are consistent with all accelerator constraints and red points have a neutralino thermal relic abundance corresponding to the inferred cosmological dark matter density (blue points have a lower thermal relic density, and we assume that neutralinos still comprise all of the dark matter in virtue of additional non-thermal production processes). The lines indicate the Fermi 95% upper limits obtained from likelihood analysis on the selected dwarfs given in Table 4.

Figure 1: Upper limits on WIMP annihilation cross section for annihilation into $\gamma \bar{\gamma}$ channel evaluated at $m_{\text{WIMP}}/3$. The expected thermal WIMP cross-section is plotted as a reference. The limits are set for masses below $1$ GeV only; limits for mass points above $1$ GeV are expected to be reliable. An update for low masses is forthcoming.

4. Discussion and outlook

Stacking analysis of 6 dSphs has been presented using a combined likelihood approach. Limits improve with respect to the most stringent of the 6 individual limits depending on WIMP mass. Some tests on consistency under choice of ROI fit range and binning have been performed. The results presented here are preliminary. The inclusion of systematic uncertainties is in progress. More dSphs will be added if they are sufficiently nearby, if relatively accurate estimates of their $\bar{M}$ distribution can be obtained, and if they are situated at sufficiently high galactic latitude to avoid galactic foregrounds. The analysis will be updated for more recent data, more annihilation channels will be studied, and a paper is in preparation within the Fermi-LAT collaboration.

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Segue 1: The Darkest Galaxy

**Fig. 2.** (a) Color-magnitude diagram of observed stars in Segue 1. The large black circles represent stars identified as radial velocity members of the galaxy using our subjective approach, the small black dots represent stars identified as non-members, and the magenta crosses are spectroscopically confirmed background galaxies and quasars. The red curve shows the location of the red giant branch, subgiant branch, and main sequence turnoff populations in the globular cluster M92 and the cyan curves show the location of the horizontal branch of M13, both corrected for Galactic extinction and shifted to a distance of 23 kpc (data from Clem et al. 2008). (b) Spatial distribution of observed stars in Segue 1. Symbols are the same as in (a), and the ellipse represents the half-light radius of Segue 1 from Martinez (2008). (c) Velocity histogram of observed stars in Segue 1. Velocities are corrected to the heliocentric reference frame. The filled red histogram represents stars classified as members, and the hatched black-and-white histogram represents non-members. The velocity bins are 2 km s$^{-1}$ wide.

**Fig. 3.** (a) Distribution of observed stars in velocity and radius. Filled red points represent stars that pass the color and magnitude selection (at either high or low priority) described in §2.2, and open black points are stars that lie outside that selection region. Stars that have been observed multiple times are plotted with their weighted average values. Segue 1 stands out as the area of high star density near $v_{hel} = 200$ km s$^{-1}$ extending out to a radius of $\sim 13$′. Based on the distribution of Milky Way stars, it is clear that the small radii ($r \leq 7$′) there is contamination of the Segue 1 members sample. In addition to Segue 1, there is also a distinct concentration of stars near $300$ km s$^{-1}$. (b) Distribution of observed stars in velocity and reduced Ca triplet equivalent width, a proxy for metallicity. As in the left panel, a large fraction of the Segue 1 members separate cleanly from the Milky Way foreground population. At $W' > 5$˚ A, the distributions begin to overlap, and unambiguously classifying individual stars as members or nonmembers becomes more difficult. Fortunately, relatively few stars are located in this region. It is clear that Segue 1 is more metal-poor than the bulk of the foreground population, although $W'$ is a much less accurate metallicity indicator for main sequence stars than giants. The $300$ km s$^{-1}$ structure appears to be more enriched than Segue 1.

The measured velocities. These calculations are a natural generalization of the Walker et al. (2009b) EM method. The method is described in more detail in Paper II and is summarized here in §5. In this framework, we find 53 definite members ($\langle p \rangle \geq 0.9$) and 9 further probable members ($0.8 \leq \langle p \rangle < 0.9$), plus the 2 RR Lyrae variables (see §4.2), but 7 of the stars considered likely members by the other two techniques receive lower probability values.
Figure 6: Annihilation cross section ULs from Segue 1 MAGIC data considering neutralino annihilating entirely into $b\bar{b}$ or into $\tau^+\tau^-$. mSUGRA models with a relic density within 3σ WMAP from the WMAP value are plotted (black crosses). Among these, neutralinos annihilating mainly in $b\bar{b}$ and $\tau^+\tau^-$ are indicated with light brown points and blue points respectively. The dashed brown line indicates ULs for a neutralino annihilating entirely into $b\bar{b}$ while the solid blue lines the case of annihilations into $\tau^+\tau^-$. The blue thin line represents the integral UL for the $\tau^+\tau^-$ channel as if they were calculated (independently of the mass) with a fixed energy threshold of 100 GeV, while for the thick blue line the energy threshold is optimized for each value of $m_\chi$. Finally, for annihilations into $\tau^+\tau^-$, the blue band covers the 2σ uncertainty on $J_\Theta(\Delta\Omega)$. Neutralinos that co-annihilate with stops and staus, or the "tail" at low masses (around 50 GeV). Among the models compatible with WMAP bounds, two representative subsets are also shown using a different color coding according to their main annihilation channel (light brown points for branching ratio $B(b\bar{b}) > 0.85$, and blue points for $B(\tau^+\tau^-) > 0.7$), which are representatives of a soft and hard gamma-ray spectrum respectively (see figure 7).

For each DM model in the scan, the integral flux UL $\Phi_{UL}(>E_0)$ can be computed following eq. (3.3), using the Segue 1 data and the specific gamma-ray spectrum of the thermal relic.
Proper motions


Kaplinghat & Strigari ApJL 2008
Outlook

- Rich Physics on scales of Galaxy
  - Dark Matter and Baryonic
- Why do low mass galaxies form in particular halos?
  - Can we find the "dark" halos?
- Wide ranging observations required